REPORT DOCUMENTATION PAGE

Form Approved OMB NO. 0704-0188

1. REPORT DATE (DD-MM-YYYY)	2. REPORT TYPE	3. DATES COVERED (From - To)
28-07-2011	Conference Proceeding	-

4. TITLE AND SUBTITLE	
A Generalized Information Matrix Fusion Based Heterogeneous Track-to-Track Fusion Algorithm	5a. CONTRACT NUMBER W911NF-10-1-0369
	5b. GRANT NUMBER
	5c. PROGRAM ELEMENT NUMBER 611102
6. AUTHORS X. Tian, Y. Bar-Shalom, T. Yuan, E. Blasch, K. Pham, G. Chen	5d. PROJECT NUMBER
	5e. TASK NUMBER
	5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAMES AND ADDRESSES	8. PERFORMING ORGANIZATION REPORT NUMBER
University of Connecticut - Storrs Office for Sponsored Programs University of Connecticut Storrs, CT 06269 -1133	
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES) U.S. Army Research Office P.O. Box 12211 Research Triangle Park, NC 27709-2211	10. SPONSOR/MONITOR'S ACRONYM(S) ARO 11. SPONSOR/MONITOR'S REPORT NUMBER(S) 57823-CS.18

12. DISTRIBUTION AVAILIBILITY STATEMENT

Approved for public release; distribution is unlimited.

13. SUPPLEMENTARY NOTES

The views, opinions and/or findings contained in this report are those of the author(s) and should not contrued as an official Department of the Army position, policy or decision, unless so designated by other documentation.

14. ABSTRACT

The problem of Track-to-Track Fusion (T2TF) is very important for distributed tracking systems. It allows the use of the hierarchical fusion structure, where local tracks are sent to the fusion center (FC) as summaries of local information about the states of the targets, and fused to get the global track estimates. Compared to the centralized measurement-to-track fusion (CTF), the T2TF approach has low communication cost and is more suitable for practical implementation. Although having been widely investigated in the literature, most T2TF

15. SUBJECT TERMS

Tracking, Heterogenous Track-to-Track Fusion

16. SECURITY CLASSIFICATION OF: a. REPORT	b. ABSTRACT	c. THIS PAGE	17. LIMITATION OF ABSTRACT	15. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
UU	UU	UU	UU		Yaakov Bar-Shalom
					19b. TELEPHONE NUMBER 860-486-4823

Standard Form 298 (Rev 8/98)
Prescribed by ANSI Std. Z39.18

Report Title

A Generalized Information Matrix Fusion Based Heterogeneous Track-to-Track Fusion Algorithm

ABSTRACT

The problem of Track-to-Track Fusion (T2TF) is very important for distributed tracking systems. It allows the use of the hierarchical fusion structure, where local tracks are sent to the fusion center (FC) as summaries of local information about the states of the targets, and fused to get the global track estimates. Compared to the centralized measurement-to-track fusion (CTF), the T2TF approach has low communication cost and is more suitable for practical implementation. Although having been widely investigated in the literature, most T2TF algorithms dealt with the fusion of homogenous tracks that have the same state of the target. However, in general, local trackers may use different motion models for the same target, and have different state spaces. This raises the problem of Heterogeneous Track-to-Track Fusion (HT2TF). In this paper, we propose the algorithm for HT2TF based on the generalized Information Matrix Fusion (GIMF) to handle the fusion of heterogenous tracks in the presence of possible communication delays. Compared to the fusion based on the LMMSE criterion, the proposed algorithm does not require the crosscovariance between the tracks for the fusion, which greatly simplify its implementation. Simulation results show that the proposed HT2TF algorithm has good consistency and fusion accuracy.

Conference Name: Proc. SPIE Conf. on Signal Processing, Sensor Fusion, and Target Recognition, #8050-41

Conference Date: April 01, 2011

A Generalized Information Matrix Fusion Based Heterogeneous Track-to-Track Fusion Algorithm*

Xin Tian[a], Yaakov Bar-Shalom[a], Ting Yuan[a], Erik Blasch[b], Khanh Pham[c] and Genshe Chen[d]

[a]Dept. of Electrical and Computer Engineering, Univ. of Connecticut, Storrs, CT, USA
[b]Sensors Directorate, Air Force Research Laboratory, Wright-Patterson AFB, OH, USA
[c]Space Vehicles Directorate, Air Force Research Laboratory, Kirtland AFB, NM, USA
[d]DCM Research Resources LLC, 14163 Furlong Way, Germantown, MD, USA

ABSTRACT

The problem of Track-to-Track Fusion (T2TF) is very important for distributed tracking systems. It allows the use of the hierarchical fusion structure, where local tracks are sent to the fusion center (FC) as summaries of local information about the states of the targets, and fused to get the global track estimates. Compared to the centralized measurement-to-track fusion (CTF), the T2TF approach has low communication cost and is more suitable for practical implementation. Although having been widely investigated in the literature, most T2TF algorithms dealt with the fusion of homogenous tracks that have the same state of the target. However, in general, local trackers may use different motion models for the same target, and have different state spaces. This raises the problem of Heterogeneous Track-to-Track Fusion (HT2TF). In this paper, we propose the algorithm for HT2TF based on the generalized Information Matrix Fusion (GIMF) to handle the fusion of heterogenous tracks in the presence of possible communication delays. Compared to the fusion based on the LMMSE criterion, the proposed algorithm does not require the crosscovariance between the tracks for the fusion, which greatly simplify its implementation. Simulation results show that the proposed HT2TF algorithm has good consistency and fusion accuracy.

Keywords: Tracking, Heterogenous Track-to-Track Fusion

For the fusion of data from distributed sensors in a tracking system, the optimal way is the centralized measurement-to-track Fusion (CTF) where all the measurements from the local sensors need to be sent to the fusion center (FC). However, this centralized approach has high communication requirements, which makes it infeasible in most practical distributed tracking systems. An alternative approach is to have sensor measurements processed locally to form local tracks, and sent them to the FC for Track-to-Track fusion (T2TF) to obtain the global state estimates. There is no requirement on when and how often the local tracks should be sent to the FC, which significantly reduces the communication requirement in distributed tracking systems. Unlike the CTF where the measurement errors are usually independent of the errors of the track estimates, local tracks have correlated errors with each other due to the common process noises [3] and information feedback [12]. Based on the formula in [3], the algorithm for the T2TF was studied in [4], where the algorithm for fusion without memory and no information feedback (T2TFwoMnf) operating at an arbitrary rate was derived. In [7], a set of fusion rules for the optimal linear estimation fusion was proposed assuming known covariances and crosscovariances among the estimates. The complete information configurations of the T2TF, including T2TF with or without memory and with no, partial or full information feedback were presented in [12]. For fusion at arbitrary rates, the exact fusion algorithms for these information configurations were derived under the assumption that the tracks are synchronized and linear Gaussian. The impact of information feedback was also investigated where it was shown that information feedback has a negative impact on the fusion accuracy of the T2TF without memory and has a positive impact on T2TF with memory. The major drawback of the exact T2TF algorithms is that the crosscovariances among the local tracks are in general difficult to obtain. The complexity of the fusion

* Research sponsored under ARO W911NF-06-1-0467 and ONR N00014-10-1-0029 grants. Proc. SPIE Conf. on Signal Processing, Sensor Fusion, and Target Recognition, #8050-41, Orlando, Apr. 2011.

Further author information: (Send correspondence to Xin Tian and Yaakov Bar-Shalom)
Xin Tian: E-mail: xin.tian@engr.uconn.edu, Telephone: 1 860 576 1941
Yaakov Bar-Shalom: E-mail: ybs@engr.uconn.edu

algorithms drastically increases with the number of local trackers. Asynchronous tracks and local tracks with communication delays further complicates the implementation of the exact fusion algorithms [13]. For these reasons suboptimal T2TF algorithms with reduced complexity and little loss in fusion performance are more desirable for practical systems.

The Information Matrix Fusion (IMF) first proposed in [8, 10] belongs to the fusion with memory [13]. It was shown to be optimal for T2TF at full rate for fusion with or without information feedback [6, 15]. The major advantage of the IMF over the optimal T2TF is that it does not require the crosscovariances among the local tracks, which greatly simplifies the fusion algorithm. The IMF can be heuristically extended to fusion at a lower rate and it was shown to be robust and to yield close to optimal fusion performance over the practical range of process noise levels [9]. In [13], the IMF was further generalized to handle the fusion of asynchronous and out of sequence tracks for the information configuration of fusion with partial and full information feedback. In a tracking scenario with a linear motion model, these algorithms compared to the CTF were shown to have good consistency and little loss in accuracy.

All the work above (as well as many others) on T2TF assume that the trackers use the same motion model for the same target and the tracks to be fused are homogenous, namely the track estimates are in the same state space. However this is not true in general. Local trackers in a distributed track system may use different motion models, e.g., due to different observability offered by their local measurements to the target state. This will result in heterogenous tracks for the same target and raises the problem of heterogenous track-to-track fusion (HT2TF), which has been rarely treated in the literature. As for the fusion of homogenous tracks, one way for HT2TF is to figure out the crosscovariance between the tracks and perform fusion based on the Linear Minimum Mean Square Error (LMMSE) criterion. However because the trackers assume different motion models for the target, the exact crosscovariance between the tracks cannot be obtained. An approximate evaluation of the crosscovariance due to common process noises (implying fusion with no memory and no information feedback [12]) was presented in [5], which uses the worst case crosscovariance that will yield a conservative fusion covariance to avoid overly optimistic fusion results. In [14] the approximation of the crosscovariance between tracks from an Interacting Multiple Model (IMM) tracker [1] and a tracker with angle and angle rate state using azimuth only measurements from a passive sensor were studied. For the information configuration considered, which is fusion with no memory and no information feedback, it was shown that accounting for the crosscovariance between the tracks offered little benefit in fusion performance. Another result that is particularly interesting in the same paper is that, when an IMM tracker is involved, the HT2TF approach may yield better fusion performance compared to the centralized measurement-to-track fusion (CTF), because angle only measurements offer little information about the true mode of the target motion and may counterproductively confuse the centralized IMM tracker.

In this paper we extend the general IMF from [13] to the problem of asynchronous T2TF to handle the fusion of heterogenous tracks. Unlike the fusion algorithm based on the LMMSE criterion, this IMF based approaches do not require the crosscovariance between tracks, which greatly simplifies the fusion algorithm, facilitates the use of information feedback and will be shown to yield desirable fusion performance.

The paper is organized as follows. Sec. 1 formulates the heterogenous track-to-track fusion problem. Sec. 2 presents the generalized information matrix fusion based HT2TF algorithms. The performance of the proposed algorithms are demonstrated by simulations in Sec. 3. Sec. 4 provides the concluding remarks.

1. PROBLEM FORMULATION

The generic heterogeneous T2TF problem for the HT2TF between two trackers can be formulated as follows.[†] Let x^1 denote the state vector used by tracker 1 which has a higher dimension state model for the target than tracker 2. As in [14], tracker 2 estimates a nonlinear transformation of x^2, namely,

$$x^2 = g(x^1) \tag{1}$$

[†]For the HT2TF with multiple trackers, the fusion algorithm is the same as in this generic two tracker case.

The dimension n_1 of x^1 is larger than the dimension n_2 of x^2.[‡] It is assumed that tracker 1 is collocated with the FC and tracker 2 is a remote local tracker whose communication with the FC is subject to random delays.

The HT2TF algorithm developed in the sequel is based on the generalized information matrix fusion (GIMF) approach which belongs to the information configuration of fusion with memory (T2TFwM)[12]. In this paper we focus on the configuration of T2TFwM with partial information feedback (T2TFwMpf), where only tracker 1 receives and continues with the fused track after the HT2TF. This configuration we believe is of the most practical interest for distributed tracking systems with heterogenous tracks. In the configuration of fusion with no information feedback, both trackers have no access to the fusion results and the fusion algorithm can be obtained from the partial feedback case with minor modification. In the configuration of T2TFwM with full information feedback, the fused tracks will be sent back to both trackers. However, in the case of HT2TF tracker 2 only reports local track information to the FC. When needed, the algorithm for HT2TF with full information feedback can be obtained according to the information flow chart for AT2TF with full information feedback in [13].

2. GENERALIZED INFORMATION MATRIX FUSION BASED ALGORITHM FOR HT2TF WITH PARTIAL INFORMATION FEEDBACK

In this configuration tracker 1 is assumed collocated with the FC, with instantaneous two-way communication between them. Tracker 2 is remote from the FC (thus its information reaches the FC with a delay) and receives no feedback from the FC. Consequently this is a T2TFwMpf Configuration [2]. First we review the generalized IMF (GIMF) for the problem of Asynchronous T2TF (AT2TF). Without loss of generality, consider the fusion of track 1 at the FC and a delayed local track from tracker 2. Suppose one has

- track $\left\{\hat{x}^1(t_f|t_f), P^1(t_f|t_f)\right\}$ from tracker 1 (same as FC) and
- tracks $\left\{\hat{x}^2(t_1|t_1), P^2(t_1|t_1)\right\}$ and $\left\{\hat{x}^2(t_2|t_2), P^2(t_2|t_2)\right\}$ from tracker 2, $t_1 < t_2 \leq t_f$.

where t_1 is the most recent time from which $\left\{\hat{x}^1(t_1|t_1), P(t_1|t_1)\right\}$ was incorporated at the FC and t_2 is the time from which $\left\{\hat{x}^1(t_2|t_2), P(t_2|t_2)\right\}$ is to be incorporated at t_f into the fused track. Assume all the above are homogenous tracks originated from the same target, i.e., both are estimating the same state. The fused track $\{\hat{x}(t_f), P(t_f)\}$at t_f according to the GIMF, is given by

$$P(t_f)^{-1} = P^1(t_f|t_f)^{-1} + \left[P^2(t_f|t_2)^{-1} - P^2(t_f|t_1)^{-1}\right] \tag{2}$$

$$\begin{aligned} P(t_f)^{-1}\hat{x}(t_f) &= P^1(t_f|t_f)^{-1}\hat{x}^1(t_f|t_f) \\ &\quad + \left[P^2(t_f|t_2)^{-1}\hat{x}^2(t_f|t_2) - P^2(t_f|t_1)^{-1}\hat{x}^2(t_f|t_1)\right] \end{aligned} \tag{3}$$

which contains the information from $\left\{\hat{x}^1(t_f|t_f), P^1(t_f|t_f)\right\}$ and the information gain $\{Z^2\}_{t_1}^{t_2}$ from track 2, which is due to the local measurement during $t_1 < t \leq t_2$ and quantified by the expression in the brackets in (2). For fusion, the information gain from track 2 is treated as independent from track 1. While the GIMF defined by (2)–(3) is not optimal[§], the above fusion algorithm was shown to yield consistent and nearly optimal fusion results in [13].

For the fusion of heterogenous tracks, suppose one has track $\left\{\hat{x}^1(t_f|t_f), P^1(t_f|t_f)\right\}$ at the FC, and tracks $\left\{\hat{x}^2(t_1|t_1), P^2(t_1|t_1)\right\}$ and $\left\{\hat{x}^2(t_2|t_2), P^2(t_2|t_2)\right\}$ from tracker 2, $t_1 < t_2 \leq t_f$, and the true states of the target satisfy (1).

From the GIMF, the information gain from track 2 due to local measurements $\{Z^2\}_{t_1}^{t_2}$ can be projected to the fusion time t_f as

$$R(t_f)^{-1} = P^2(t_f|t_2)^{-1} - P^2(t_f|t_1)^{-1} \tag{4}$$

[‡]A concrete example of such a situation is when (i) tracker 1 uses an active sensor and its target state vection comprises Cartesian position and velocity (ii) tracker 2 uses a passive sensor and its target state vector comprises angular position & velocity.

[§]The optimality of the IMF requires the fusion to be performed at every time when any of the tracks is updated [2], namely track-to-track fusion at full rate.

Here it is assumed that $R(t_f)^{-1}$ in (4) is invertible, which is satisfied in most cases.¶ Let

$$z^2(t_f) = R(t_f)\left[P^2(t_f|t_2)^{-1}\hat{x}^2(t_f|t_2) - P^2(t_f|t_1)^{-1}\hat{x}^2(t_f|t_1)\right] \tag{5}$$

which is the equivalent measurement that, with its associated covariance $R(t_f)$, summarizes the information gain between local tracks $\{\hat{x}^2(t_1|t_1), P^2(t_1|t_1)\}$ and $\{\hat{x}^2(t_2|t_2), P^2(t_2|t_2)\}$.

For the fusion, the covariance of the fused track is given by

$$\begin{aligned} P(t_f)^{-1} &= P^1(t_f|t_f)^{-1} + G(t_f)'\left[P^2(t_f|t_2)^{-1} - P^2(t_f|t_1)^{-1}\right]G(t_f) \\ &= P^1(t_f|t_f)^{-1} + G(t_f)'R(t_f)^{-1}G(t_f) \end{aligned} \tag{6}$$

where $G(t_f)$ is the $(n_2 \times n_1)$ Jacobian of $g(x^1)$, i.e.,

$$G(t_f) = \left[\nabla_{x^1}\left(g(x^1)\right)'\right]'_{x^1=\hat{x}^1(t_f|t_f)} \tag{7}$$

Let

$$W(t_f) = P(t_f)G(t_f)'R(t_f)^{-1} \tag{8}$$

The fused track estimate is given by

$$\hat{x}(t_f) = \hat{x}^1(t_f|t_f) + W(t_f)\left[z^2(t_f) - g\left(\hat{x}^1(t_f|t_f)\right)\right] \tag{9}$$

which amounts to fusing the information gain (summarized by $z^2(t_f)$ and $R(t_f)$) from track 2 with the central track as if they had uncorrelated errors. While this uncorrelatedness assumption is an approximation it was shown in [13] to perform remarkably well.

3. SIMULATION RESULTS

To show the performance of the proposed HT2TF algorithm consider a basic tracking scenario in 2-D with two trackers. Tracker 1 and the FC are located at the origin. It uses an active sensor (which measures full position) and a (discretized) Continuous White Noise Acceleration (CWNA) motion model [1] for the target with the state in the Cartesian coordinates as

$$x^1 = [\xi\ \dot{\xi}\ \zeta\ \dot{\zeta}]' \tag{10}$$

and

$$x^1(k+1) = Fx^1(k) + v(k) \tag{11}$$

where

$$F = \begin{bmatrix} 1 & T_1 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & T_1 \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{12}$$

and

$$Q = \mathrm{E}[v(k)v(k)'] = \begin{bmatrix} \frac{1}{3}T_1^3 & \frac{1}{2}T_1^2 & 0 & 0 \\ \frac{1}{2}T_1^2 & T_1 & 0 & 0 \\ 0 & 0 & \frac{1}{3}T_1^3 & \frac{1}{2}T_1^2 \\ 0 & 0 & \frac{1}{2}T_1^2 & T_1 \end{bmatrix}\tilde{q} \tag{13}$$

¶This requires the full observability of the target state form the local measurement set $\{Z^2\}_{t_1}^{t_2}$, which is satisfied for fusion at a lower rate when the number of measurements in $\{Z^2\}_{t_1}^{t_2}$ is larger than the observability index [2]. When $R(t_f)^{-1}$ is singular a linear projection of the information gain can be used to guarantee the invertibility, which is not presented in the paper for the sake of conciseness.

with $\tilde{q}$ the PSD of the continuous process noise, discretized as $v(k)$ with sampling interval T_1. The above is also the true motion model followed by the target. The tracker receives range and azimuth measurements of the target with period T_1. The measurements are assumed to have zero mean Gaussian errors with standard deviations σ_r and σ_a, respectively. An Extended Kalman filter (EKF) [1] is used for the track update.

The remote local tracker 2 is located at (X_2, Y_2) was a passive sensor and receives angle (Direction Of Arrival) only measurements with period T_2 with errors that are zero mean Gaussian with standard deviation σ_{a_2}. This tracker uses angle and angle rate as the target state, namely,

$$x^2 = [\beta\ \dot{\beta}]' \tag{14}$$

where β is the azimuth of the target w.r.t. tracker 2. The state equation is

$$x^2(k+1) = \begin{bmatrix} 1 & T_2 \\ 0 & 1 \end{bmatrix} x^2(k) + v_a(k) \tag{15}$$

with

$$Q_a = \mathrm{E}[v_a(k)v_a(k)'] = \begin{bmatrix} \frac{1}{3}T_2^3 & \frac{1}{2}T_2^2 \\ \frac{1}{2}T_2^2 & T_2 \end{bmatrix} \tilde{q}_a \tag{16}$$

where $\tilde{q}_a$ is the PSD of the continuous process noise used by tracker 2.

In the simulation the following set of parameters is used. For tracker 1, $\sigma_r = 10\,\mathrm{m}$, $\sigma_a = 1^o$, $T_1 = 3\,\mathrm{s}$, $\tilde{q} = 10^{-2}\,\mathrm{m}^2/\mathrm{s}^3$; For tracker 2, $(X_2, Y_2) = (1500, 2500)\,\mathrm{m}$, $\sigma_{a_2} = 0.1^o$, $T_2 = 3.5\,\mathrm{s}$, $\tilde{q}_a = 10^{-5}\,\mathrm{rad}^2/\mathrm{s}^3$. Tracker 2 sends its local track to the FC at [22, 64, 106, 148, 190, 232]s which arrive at the FC after a communication delay of 3 s. Fig. 1 shows the trackers (sensors) and target geometry in the simulation.

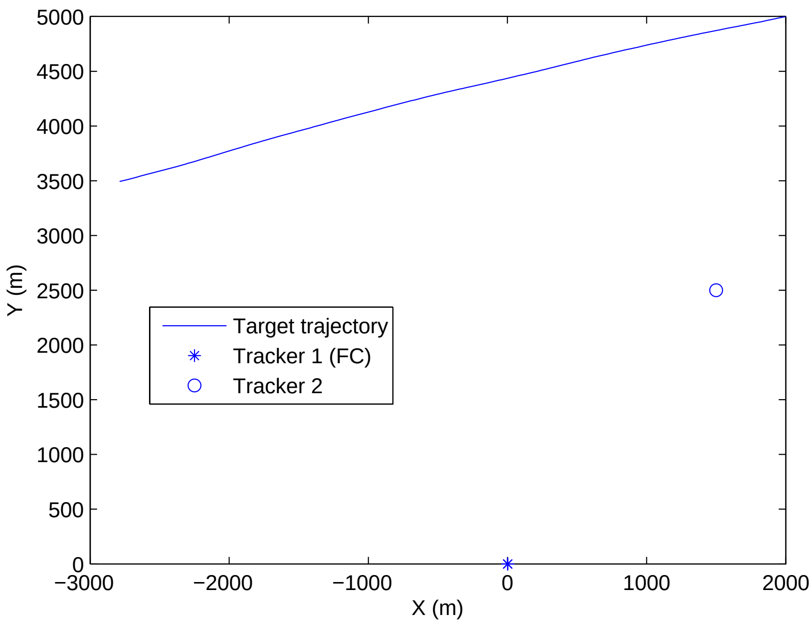

Figure 1. The simulation scenario.

The following simulation results were obtained from 100 Monte Carlo runs. Figs. 2–3 show the performance of the local tracker 2. It can be seen that this tracker is consistent.

Figs. 4–5 compare the tracking performance of tracker 1 operating by itself and with the HT2TF with memory and partial information feedback (HT2TFwMpf). It can be seen that the proposed fusion algorithm is consistent

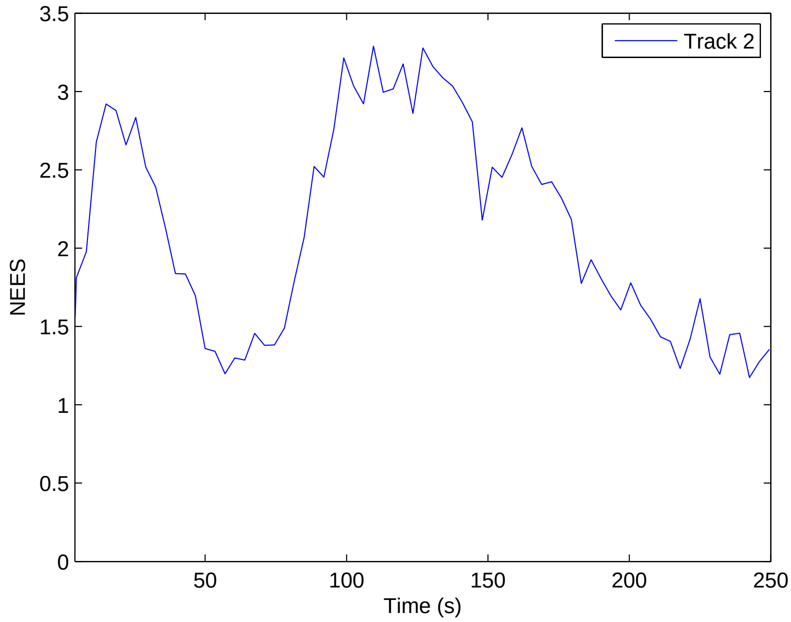

Figure 2. Consistency test (Normalized Estimation Error Squared) of track 2. (ideal value of NEES is 2)

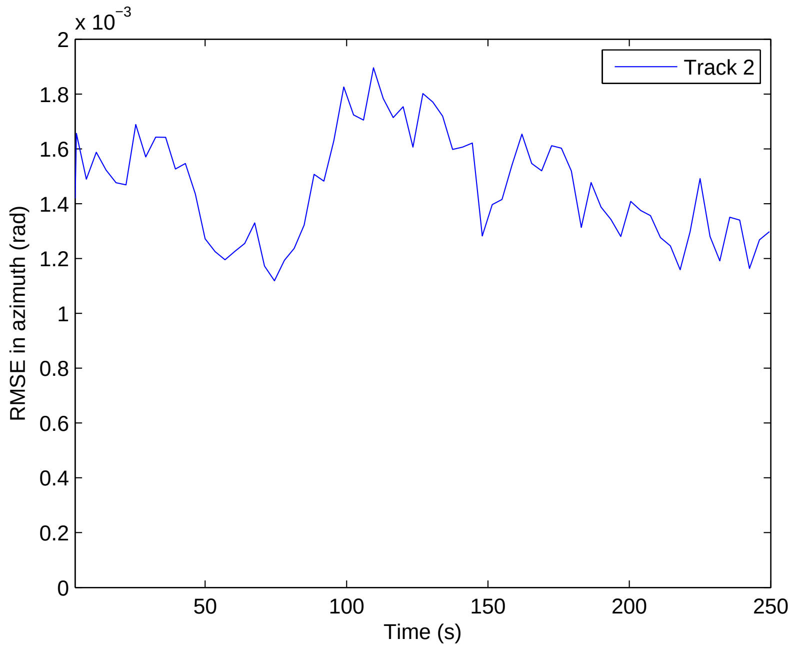

Figure 3. Tracking accuracy of track 2.

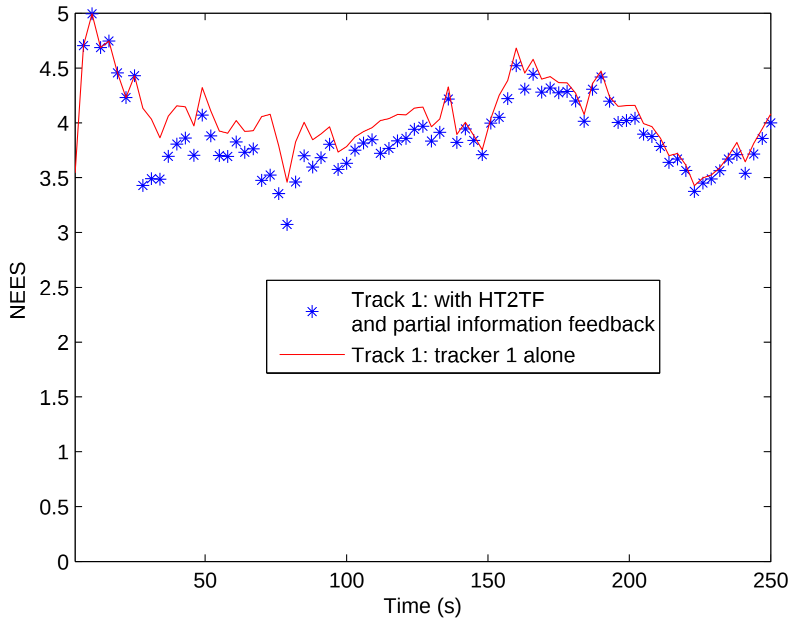

Figure 4. Consistency test of tracker 1 with and without HT2TFpf

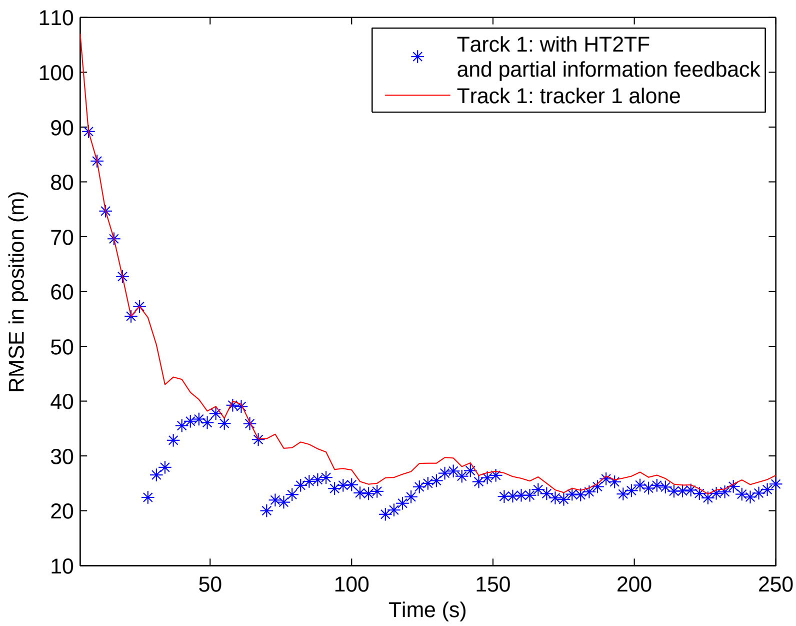

Figure 5. Tracking accuracy of tracker 1 with and without HT2TFwMpf. (ideal value of NEES is 4)

and, by incorporating the information from the heterogenous local track 2, track 1 has significant gain in tracking accuracy, especially at the early stage of the filtering when track 1 was less accurate without the feedback and tracker 2 was close to the target.

4. CONCLUSIONS

The paper presented an algorithm for the fusion of heterogenous tracks (HT2TF), based on an extension of the generalized information matrix fusion (GIMF) for the problem of asynchronous track-to-track fusion. Similarly to the Information Matrix Fusion (IMF), this fusion algorithm does not need the crosscovariance between the heterogenous tracks for the fusion. Instead, the information gain from the local track is fused with the central track as if they were independent, which greatly simplifies the fusion algorithm. The proposed fusion algorithm has no limit on the number of local trackers and allows the use of information feedback. Simulation results show that this algorithm has good consistency and excellent fusion accuracy.

REFERENCES

[1] Y. Bar-Shalom, X. R. Li and T. Kirubarajan, *Estimation with Applications to Tracking and Navigation: Algorithms and Software for Information Extraction*, Wiley, 2001.

[2] Y. Bar-Shalom, P. K. Willett and X. Tian, *Tracking and Data Fusion*, YBS Publishing, 2011.

[3] Y. Bar-Shalom, “On the Track-to-Track Correlation Problem,” *IEEE Trans on Automatic Control*, 26(2):571–572, April 1981.

[4] Y. Bar-Shalom and L. Campo, “The Effect of the Common Process Noise on the Two-Sensor Fused-Track Covariance,” *IEEE Trans on Aerospace and Electronic Systems*, 22(6):803–804, Nov. 1986.

[5] H. Chen and Y. Bar-Shalom, “Track Association and Fusion with Heterogeneous Local Trackers,” *Proc. 46th IEEE Conf. on Decision and Control*, New Orleans, LA, Dec.2007

[6] K. C. Chang, R. K. Saha and Y. Bar-Shalom, “On Optimal Track-to-Track Fusion,” *IEEE Transactions on Aerospace and Electronic Systems*, 33(4):1271–1276, Oct. 1997.

[7] X. R. Li, Y. M. Zhu, J. Wang and C. Z. Han, “Unified Optimal Linear Estimation Fusion–PartI: Unified Model and Fusion Rules,” *IEEE Transactions on Information Theory*, 49(9):2192–2207, Sept 2003.

[8] C. Y. Chong, “Hierarchical estimation”, *Proc. of MIT/ONR Workshop on C3*, 1979.

[9] K. C. Chang, Z. Tian, and R. Saha, “Performance Evaluation of Track Fusion with Information Matrix Filter,” *IEEE Trans. on Aerospace and Electronic Systems*, 38(2):455–466, April 2002.

[10] J. L. Speyer, “Computation and transmission requirements for a decentralized linear-quadratic-Gaussian control problem”, *IEEE Transactions on Automatic Control*, 2(2):54–57, Apr. 1979.

[11] H. Chen and Y. Bar-Shalom, “Track Association and Fusion with Heterogeneous Local Trackers”, *Proc. 46th IEEE Conf. on Decision and Control*, New Orleans, LA, Dec. 2007.

[12] X. Tian, Y. Bar-Shalom, “Exact algorithms for four track-to-track fusion configurations: All you wanted to know but were afraid to ask,” *Proc. 12th International Conference on Information Fusion*, Seattle, WA, USA, July 2009.

[13] X. Tian and Y. Bar-Shalom, “Algorithms for Asynchronous Track-to-Track Fusion”, *J. of Advances in Information Fusion*, 5(2)128:138, Dec. 2010.

[14] T. Yuan, Y. Bar-Shalom and X. Tian, “Heterogeneous Track-to-Track Fusion”, *Proc. 14th Intn'l Conf. on Information Fusion*, Chicago, IL, July 2011.

[15] Y. M. Zhu Z. You, J. Zhao, K. Zhang and X. R. Li, “The optimality for the distributed Kalman ”ltering fusion with feedback”, *Automatica* 37:1489-1493, 2001.